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NASA Technical Memorandum 82685

(NASA-TM-82685) SOLAR CELL DEVELOPMENT FOR THE POWER EXTENSION PACKAGE (NASA) 8 p HC A02/MF A01 CSCL 10A

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Solar Cell Development for the Power Extension Package

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Prepared for the
Sixteenth Intersociety Energy Conversion Engineering Conference
sponsored by the American Society of Mechanical Engineers
Atlanta, Georgia, August 9-14, 1981

NASA

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August 1981

Report documentation page: The performing organization report number (block 8) should be E-962.

SOLAR CELL DEVELOPMENT FOR THE POWER EXTENSION PACKAGE*

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ABSTRACT

The Power Extension Package (PEP) is the prime focus of a development program to produce low cost solar cells. The PEP is a 32 kilowatt flexible substrate, retrievable, solar array system for use on the Space Shuttle. Solar cell costs will be reduced by increasing cell area and simplifying cell and coverglass fabrication processes and specifications. The cost goal is to produce cells below $30 per watt. Two and ten ohm-cm silicon cells were investigated.

In Phase I of the cell development program a few thousand candidate cells will be produced and evaluated for utility and quality. In Phase II a large number of cells will be fabricated to verify production readiness and cell yields and costs. This schedule is compatible with PEP initial operational capability in 1984. Approximately 140,000 large area (5.9 x 5.9 cm) cells will be required for two PEP solar arrays.

This paper describes the status of the cell development and testing, including a unique radiation damage test and side-by-side comparison of candidate cell types with pre- and post-irradiation airplane calibration of outer space short-circuit current.

E-962

INTRODUCTION

The Power Extension Package (PEP) is a 32 kW reusable photovoltaic power supply under development by the NASA Johnson Space Center (JSC). The purpose of this paper is to describe the PEP and give an overview of cell development which is co-managed by the NASA Lewis Research Center (LeRC) and JSC.

The PEP is designed to operate from the Space Shuttle Orbiter cargo bay (figure 1) and to supplement the Orbiter's fuel cell-cryogenic power source. The Remote Manipulator System attaches PEP to the orbiter. Each solar array wing is about 150 square meters in area. The PEP is designed as a flight kit that can be easily installed in the Orbiter with minimum effect on payload processing and ground operations. The PEP offers a major increase in the Shuttle's power level and mission duration without degrading the orbital range or attitude pointing capability. The PEP more than doubles the power available to payloads and improves the Orbiter's heat rejection capability available to payloads. The PEP will weigh about 2000 lbs. In comparison, the payload weight reduction (due to adding fuel cell cryogenic fuel) to increase mission time (but not power lead) is about 1000 lb per day. Thus the PEP also offers a weight saving which will have a significant impact on payload weight.

At least two PEP systems, one for each launch site, are planned. PEP is expected to have a major impact on power launched for NASA programs (figure 2) and on silicon solar cell manufacturing.

BACKGROUND

The PEP concept was derived at JSC in 1977. A preliminary feasibility study began in 1978 and the project plan was defined in 1979. Numerous items (including the solar cell) requiring long lead time development were identified. The PEP system construction is scheduled to begin in 1981 with initial operational capability planned for 1984.

Unlike a complete spacecraft in which the solar array is only 5 to 10 percent of the total acquisition cost, PEP has few subsystems and its cost is dominated by the solar array. Current estimates show the array to be 30 to 40 percent of the PEP acquisition cost. In turn, the cost of solar cells could be as much as 40 percent of the array cost. Therefore, solar cell costs have considerable leverage in the program.

Studies performed during the project definition activity in 1979 showed the potential for significant cost reduction in solar cells. Studies performed by Applied Solar Energy Corporation (ASEC) and Solarex under subcontract to Lockheed (ref.1) showed that the potential to produce space quality solar cells for $30 per watt exists. Two primary areas which can lead to significantly lower cost are: 1) cell size and 2) cell specification and quality control provisions. The use of larger area solar cells is beneficial in two ways. First, greater use is made of the available silicon in the starting wafer and second, fewer parts have to be processed to yield the required power. In addition, fewer parts are handled in array production and costs are reduced. For example, the PEP solar array would require approximately 300,000 2x4 cm cells compared to approximately 67,000 5.9x5.9 cm of the new PEP cells. The primary purpose in modifying the cell specification is to reduce the number of redundant in process checks and the number of destructive tests required.

CELL DEVELOPMENT

In early 1980, JSC and LeRC initiated a PEP solar cell development program. The program to produce low cost solar cells for PEP attacks the problem in three phases. In Phase I, the questions to be addressed are: 1) can a large area cell be built which will perform as well as a 2x2 cm or a 2x4 cm size cell; 2) are large area 5.9x5.9 cm cells usable in flexible substrate solar arrays; and 3) is a cost goal of $30 per watt a reasonable target? In phase II a large quantity of cells will be produced to determine cell

*Includes material previously presented at the Fifteenth Photovoltaic Specialists Conference "Comparative Radiation Testing of Solar Cells for the Shuttle Power Extension Package (TM-82656) by Cosmo R. Baraona, Clifford R. Swartz, and Russell E. Hart, Jr.

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yields, cost and performance, and to demonstrate a production rate of 12,000 cells per month. These cells will be available for qualification tests. Phase III is the production of about 140,000 large area cells for two PEP systems

The program organization for Phase I is shown in figure 3. A key feature of the program is that not only are NASA and the two solar cell vendors (ASEC and Spectrolab) involved, but also TRW and Lockheed Missiles & Space Company (LMSC) are under subcontract to the cell vendors. This arrangement is used to assure that the products and the specifications to which they are manufactured are compatible with both array programs. Under this arrangement, NASA acts as an overseer with LeRC being responsible for cell technology issues and JSC being responsible for cell array systems and programmatic issues.

The cost goal for Phase I is to produce cells for $30 per watt. This cost is about one third of present space cell costs. Two primary types of baseline cells are under development: 1) a cell with a base resistivity of two ohm-cm incorporating a back surface reflector (BSR) with a thermal absorptivity (alpha) of 0.70 and 2) a ten ohm-cm cell with a back surface field (BSF) and a BSR with an alpha of 0.75. A third (two ohm-cm BSR, BSF) cell type was also evaluated for PEP mission suitability.

The electrical contact metallization system to be applied to the generic cell (i.e. base resistivity and back surface treatment) type selected will be either a wraparound with dielectric insulation or a conventional top-bottom contact. Air mass zero (AMO) efficiency goals for each contact type are 12.8% for the wraparound and 14% for the conventional cell. Either conventional (Ta_2O_5) or multilayer antireflection (AR) coatings may be used.

The final PEP system designer will select the solar cell technologies that will yield the best combination of beginning of life (BOL) and/or end of life (EOL) performance, lowest overall system cost and acceptable technical and schedular reliability and risk. The Phase I and II cell development activity will provide the information needed for that selection.

Some of the advantages and disadvantages of the various cell technologies are as follows. The base resistivity affects power output (performance), radiation degradation rate and temperature coefficient of performance. As resistivity increases, power decreases during irradiation. Use of a BSF increases BOL performance. However, this increase is lost after moderate radiation fluences. Conversely, BSF increases thermal absorptivity which raises cell operating temperature in orbit thus reducing performance. On the other hand, BSR reduces thermal absorptivity and operating temperature and thus increases performance. Both BSR and BSF add to the complexity and cost of the cell. AR coating type affects power output, temperature coefficient and cell cost. There is thus a multitude of effects which mandates side by side comparative development and testing.

The cell development efforts at Spectrolab (ref. 3) and at ASEC (ref. 4) have addressed a wide range of similar, though not identical issues. Some of the development efforts are as follows: 1) investigation of alternate cell technologies and processing techniques, 2) optimization of cell design and manufacturing process, 3) equipment and tooling design and construction, 4) acceptance and approval type testing, 5) generation of software such as manufacturing control documents, solar cell specifications and test plans, and plans for implementing full production, 6) cell fabrication, and 7) analysis of cell costs.

The cell development contractors have shown that large area (5.9 x 5.9 cm) cells can be made and that the 12.8 and 14% performance goals can be met. Preliminary analysis indicates that the $30/watt cost goal can be achieved with optimistic but realistic assumptions of process yield.

CELL TESTING

Extensive measurements and tests of PEP cells are in progress at all the contractor facilities. These include current-voltage performance, contact reliability evaluation, optical properties, temperature coefficients, thermal cycling, environmental tests, module fabrication and process and handling tests.

The PEP array will operate in low earth orbit for a cumulative time of about 3 years and will be subjected to performance degradation by space radiation equivalent to 1 or 2×10^{14} 1 MeV electrons/cm^2. Laboratory tests to determine the amount of cell degradation due to radiation are thus necessary for proper cell selection and system design. Part of the Phase I development included radiation damage tests of candidate low-cost PEP cells conducted at the NASA-Lewis Research Center. (ref. 5)

Six different cell types with the best potential for meeting the system requirements were supplied by the two PEP cell prime contractors for evaluation. The cells had combinations of resistivity, BSR, BSF, and AR coating. The code used to describe the cells is shown in Table I.

The test conditions are also shown in Table I. Two groups of cells were irradiated. In each group, three cells of each type were randomly arranged in the test fixture. All the measured performance data were taken at 28° C. The temperature of the cells operating in orbit will be higher and will reduce the efficiency. However the orbital operating temperature and efficiency can be calculated by the PEP system designer if the thermal absorptivity (which varies depending on cell type) is known.

The cells to be used for the PEP array will be 5.9x5.9 cm in size to reduce cost. However, the cells used for this radiation damage test were 2x2 cm in size so that greater numbers of cells could be tested, thus increasing the statistical reliability of the data. As long as the small area cells have the same characteristics (material, processes, spectral response, etc.) as the large area cells and the cells are irradiated uniformly over their area, cell size is not expected to affect the radiation test results. The highest fluence attained in this test was 3×10^{14} e/cm^2 which exceeds the maximum expected for the PEP mission life.

Two methods of fluence measurement were used: A Faraday cup current integrator and control cells with known radiation degradation behavior. The maximum power of these control cells agreed well with previous data confirming the accuracy of the Faraday

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cup and the uniformity of irradiation.

After irradiation, the cells were annealed for 17 hours at 60° C in air without illumination to ensure that the measured performance would be stable. Because of the low fluences and the use of Czochralski-grown silicon, photon degradation effects were not expected; therefore the standard procedure of annealing with post irradiation illumination was not used.

The current-voltage measurements of all the cells were made with an X-25 xenon arc solar simulator. The light intensity of the simulator was adjusted until the measured short-circuit current of an aircraft-flown primary reference cell agreed with its aircraft projected air mass zero (AMO) value. The reference cells used at the start of the tests were either actual candidate PEP cells flown and calibrated specifically for this test or cells with spectral responses closely matched to the PEP cells to be tested. A good spectral response match is vital to the overall accuracy of the test. The aircraft calibration procedure is described elsewhere (ref. 6).

After irradiation to 3×10^{14} e/cm^2 the PEP cells had degraded such that their spectral response no longer closely matched the spectral response of the unirradiated reference cells. Therefore, these irradiated PEP cells were aircraft-flown and their accurate AMO short-circuit currents (I_{sc}) measured. The maximum power and I_{sc} data at all the fluences were then adjusted based on the change in calibration due to the spectral response shifts during irradiation. At the highest fluence these adjustments increased cell output over that measured with the non-irradiated standards from 1.2% to 4.4% depending on cell type. The multilayer AR coated cells required the highest adjustments. In other words, without adjustment the data could have been in error by as much as 4.4% at 3×10^{14} e/cm^2. At zero fluence, no adjustments of this type were needed. At intermediate fluences the adjustments ranged between zero (at 1×10^{13} e/cm^2) and 4.4% and were proportional to the logarithm of the fluence.

The average maximum power of each 6-cell group at each fluence for the 10 and 2 ohm-cm cells is shown in figures 4 and 5 respectively. For each point, the data spread was less than 3%. These data show that the A10FRM, (i.e. the ten ohm-cm cell with a BSF, a BSR and a multilayer AR coating) had the highest beginning of life (BOL) power (76.8 mW) under laboratory conditions. At 3×10^{14} e/cm^2 fluence, the A10FRM and the A2RM cells both had the highest average power (56.4 mW). The S2FRT, a unique 2 ohm-cm BSF cell, has about 10% higher BOL power (72.4 mW) than the S2RT (65.6 mW) due to the BSF. However, the S2FRT degrades more quickly than the S2RT and at 3×10^{14} e/cm^2, the power increase due to the BSF effect is almost completely eliminated (53.2 vs 52.8 mW). Comparison of S2FRM (73.1 mW) and S2FRT (72.4 mW) shows about a 3.7% boost in power due to the multilayer AR coating.

In terms of normalized power (i.e. maximum power at zero fluence divided by maximum power after 3×10^{14} e/cm^2) the 2 ohm-cm BSR cells degraded to 0.80 of original; the 10 ohm-cm BSR/BSF cells degraded to 0.74 and the 2 ohm-cm BSR/BSF cells degraded to 0.73 of their original power.

CONCLUSIONS

These radiation damage results are necessary, but not sufficient, information needed by the designer to select the cell to be used on PEP. These tests show that the cell type with the highest power output at room temperature was the 10FRM at BOL. The 10FRM and 2RM groups had equal power at EOL. The lower thermal absorptivity (measured elsewhere) of non-BSF cells results in lower orbital operating temperature and higher power output. Thus, the 2 ohm-cm BSR cell will have the best EOL performance in orbit. The 2RM cells also had the least change in power over mission life which aids power supply design. Additional information needed for cell selection which are still being generated include the influence of array design on operating temperature and the cell cost and delivery schedule. The radiation test results described here are a vital starting point in the cell selection process.

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TABLE 1. - CELL AND TEST DESCRIPTION

Cell Code

A	Cell manufacturer
S	Cell manufacturer
10	Base resistivity in ohm-cm
2	Base resistivity in ohm-cm
F	Back surface field
R	Back surface reflector
T	Ta_2O_5 AR coating
M	Multilayer AR coating
P 180	2 ohm-cm control cell

Number of Cells	Cell Type
3	A10FRM
3	A2RM
3	S2RM
3	S2FRT
3	S2RT
3	S10FRT
4	P180

Test Conditions

- o 1 MeV electron flux $< 10^{12}$ e/cm^2/sec in air.
- o Cell temperature 40° C during irradiation, 60° C for 17 hours in air post irradiation annealing.
- o Measurements: AMO I-V at 28° C, spectral response and aircraft calibration of AMO I_{sc}.
- o All cells 2x2x0.02 cm, no coverglass, conventional.

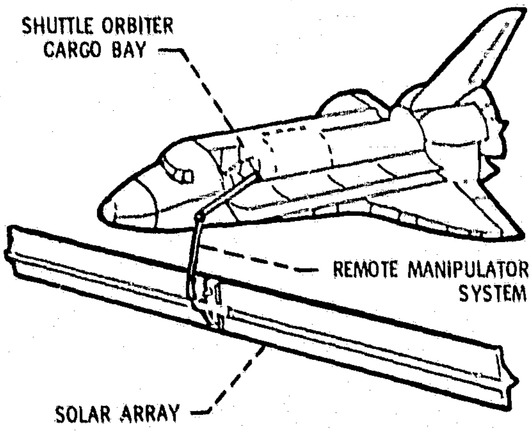

Figure 1. - PEP system with the space shuttle

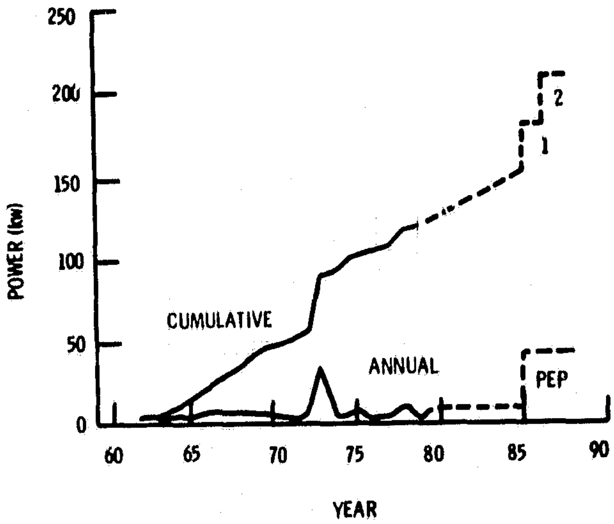

Figure 2. - Effect of PEP on solar power for NASA programs

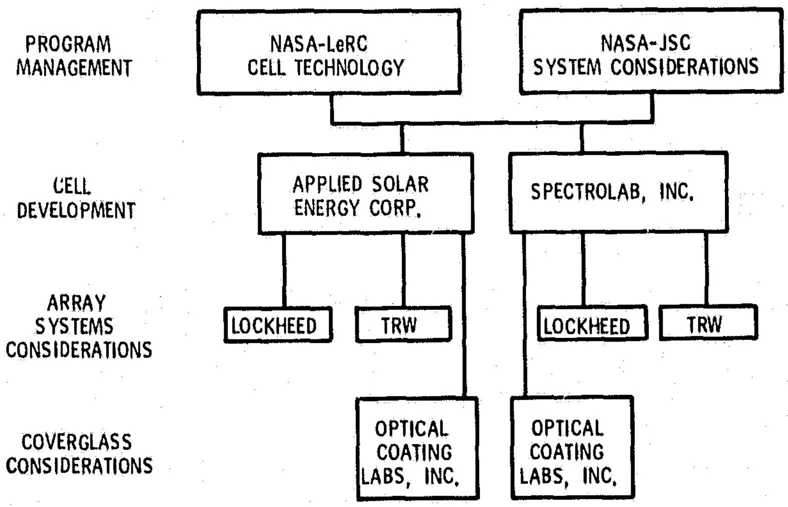

Figure 3. - Program organization for phase I PEP cell development

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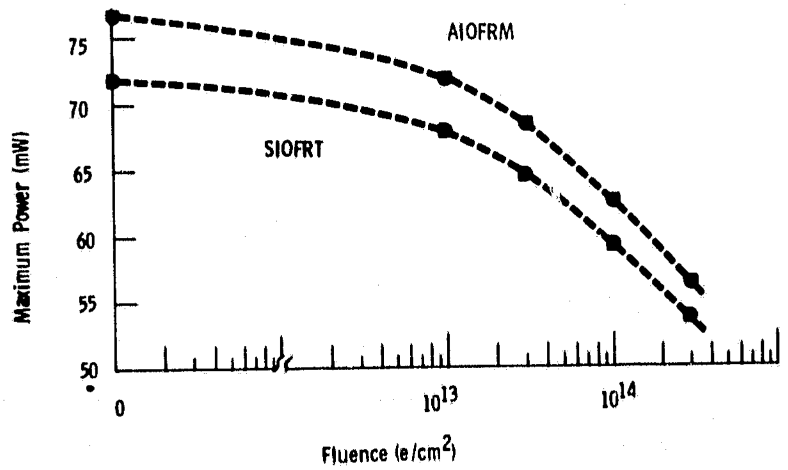

Figure 4. - Variation of maximum power with fluence for 10 ohm-cm PEP cells

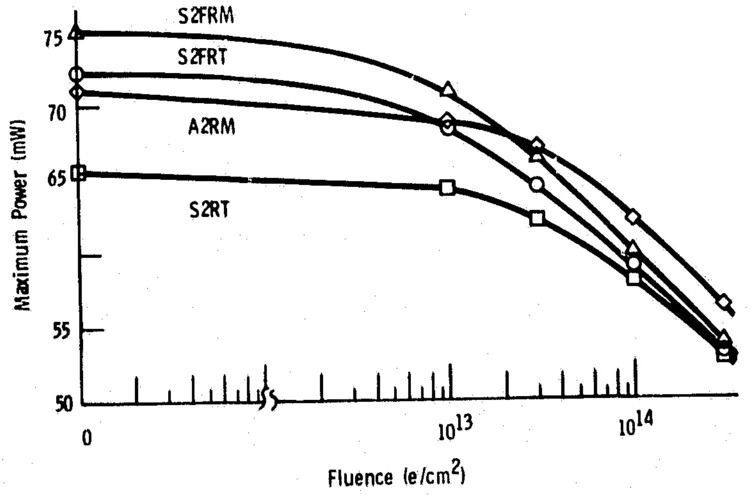

Figure 5. - Variation of maximum power with fluence for 2 ohm-cm PEP cells